RESEARCH ARTICLE

Overall Stability Analysis of Ribb Earthen Dam in Ethiopia

H. F.Gebregziabher[1], F. Gebrehiwot[2]

[1]Addis Ababa Institute of Technology, Addis Ababa University,
King George VI St, Addis Ababa, Ethiopia

[2]Arba Minch Institute of Technology, Arba Minch University, Arba Minch, Ethiopia

ABSTRACT: This study aimed at assessing the static and dynamic slope stability of Ribb Zoned Earthen Dam that is located in the earthquake prone areas of Ethiopia by employing finite element method using the shear strength reduction (SSR) technique of PLAXIS. The slope stability analyses were coupled with seepage analyses by considering different critical loading conditions. The peak ground acceleration (PGA) required as an input for the dynamic analyses of the dam were determined from a real accelerogram of an earthquake of magnitude 6.5 Richter scale recorded in 1845 around the dam, at epicenter distance of 175 km. Since the Ribb dam site and reservoir area lie in an earthquake sensitive zone of magnitudes 4.5 to 6.5, additional dynamic analyses have also been carried out corresponding to an earthquake of magnitude 4.5. The results of the coupled analyses using these two values of PGA showed that, the dam is stable at all critical conditions. Deformation analyses also showed that all displacements in the dam crest are within permissible limits.

KEYWORDS: Slope stability; Seepage analysis; Earthquake; 2D Finite element Analysis; Peak ground acceleration

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1. INTRODUCTION

Embankment dams in excess of 300 meters height with volumes of many millions of cubic meters of fill are presently being realized all over the world [1]. Detailed stability analysis of such big dams shall be carried out by considering all the probable destabilizing factors, as dam safety is a major concern to the general public [2].

Many countries have experienced frequent floods that have overtopped dams associated with dam breakage and extreme downstream flooding. Such damages are associated with various problems such as loss of social capital, large scaled economical expenses and even loss of valuable lives [3].

A dam failure can be a disastrous event with catastrophic consequences to the downstream area and the surrounding environment. Inundations from many dam failures have the potential for immense damage to property, the economy, the environment, and possibly fatalities [4].

According to the International Humanitarian Law, dams are considered "installations containing dangerous forces", since these structures have huge influence of an impending catastrophe on lives and property [5].

A storage dam subjected to rapid drawdown of reservoir should have an upstream zone with sufficient permeability to dissipate pore water pressure exerted outwards in the upstream part of the dam. Seepage analysis and stability investigation are very important issues that should be considered during the design of earth fill dams [6].

According to [7], "Excessive seepage in any type of dam is one of the root causes to destabilize the dam structure and thereby bringing economic havoc". If the phreatic line, i.e., the upper boundary of the flow under hydrostatic pressure, is allowed to intersect the downstream slope above the toe, a serious sloughing will always occur [2].

Due to extreme rainfall in 2010 in the Lusatian Neisse River catchment area, a flood event with a return period of over 100 years occurred, leading to the failure of the Niedów dam. The earth-type dam was washed away, resulting in the rapid release of nearly 8.5 million m^3 of water and the flooding of the downstream area with substantial material losses [8].

Earthquake is the other main cause that makes a dam unstable producing tremendous amount of energy [9]. There are over a million of earthquakes each year, most of which are insignificant and about 3,000 of these dynamic effects produce noticeable damages. On average, about 10,000 people die each year because of

**Corresponding Author: henok.fikre@aait.edu.et*

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earthquakes [10]. The potential earthquake source in the area of the dam need to be identified along with the greatest earthquake each source can produce and time histories representing the resulting attenuated ground motions at any dam site. In order to prevent uncontrolled rapid release of water from the reservoir of a storage dam, it should be able to withstand an extreme earthquake which is referred to as the safety evaluation earthquake (SEE) or the maximum credible earthquake (MCE) [11]. This is the greatest earthquake that could reasonably be generated by a specific seismic source, based on seismological and geological evidences and interpretations.

This research is aimed at proving the stability of Ribb Earthen dam under the action of static and dynamic loading conditions coupled with seepage. Since most earth fill dams performed badly especially against dynamic loads [11] full dynamic analysis coupled with different critical water level scenarios has been considered in this study. The stepwise construction of the dam and the loading conditions have been modelled using Finite Element Analysis (FEM) based software PLAXIS by assigning appropriate material parameters and constitutive models. The significance of the research is not only limited to the insurance of the safety of Ribb dam, which is one of the few large earthen dams in Ethiopia; but also in introducing important modelling concepts for other earthen dams of comparable conditions.

2. STUDY AREA

Ribb dam is an earthen zoned dam which is located in north western parts of Ethiopia across the Ribb River, on the eastern side of Lake Tana basin, in South Gondar zone of Amhara national regional state [12]. It is situated about 700 km from Addis Ababa. The dam was planned and constructed being part of the development plans of the Ethiopian Government in the fertile Blue Nile basin [12].

The specific geographic grid reference location of the dam site is bounded between N 12° 02' 30" and E 37° 59' 45". The dam has 800 m crest length and 73.2 m height above the river bed with crest width of 10 m and reservoir impounding about 234 million m^3 of water. According to the reports of Water Works design and supervision Enterprise, WWDSE [13], three saddle dams were also supplemented to fill a depression in both sides of the dam. The impounded water was planned to irrigate 15,000 Ha of the Fogera Plain [12]. The location of the dam is depicted in (Figure 1)

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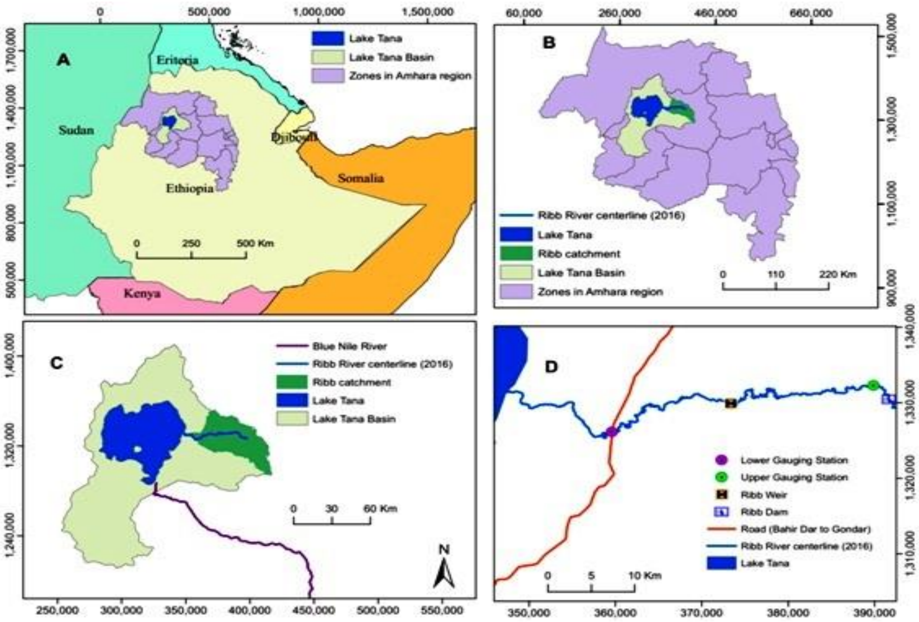

Figure 1: Location of Ribb Earthen Dam site [14]

The route of the Ribb River had experienced a series of flooding records, the damaging effects of which were tried to be minimized by constructing different embankments [15]. One of the envisaged advantages of constructing the Ribb dam is to reduce the effects of these floods resulting from the excessive sedimentation.

The materials used to construct an earth fill embankment dam are utilized to the best advantage in relation to their characteristics as an engineered bulk fill in zones within the dam section. The design slopes of the upstream and downstream embankments may vary widely, depending on the character of the materials

available, foundation conditions, height and type of the dam [16]. The Ribb dam zoning is made up of the following materials, which can also be identified on (Figure 2) and parameterized in (Table 1).

- Impervious core consisting of clay material constructed at the center of the dam having a slope of 1H: 4V. The width of clay material at the foundation is 40 m and it will be reduced to 3 m at the crest elevation.
- Filter materials F1 and F2 consisting of fine-grained materials provided on the upstream and downstream part of the dam next to the clay along the dam axis
- Shell material made of coarse-grained material next to the coarser filter
- Compacted rock materials controlling the stability of the dam and
- Riprap used for slope protection against the water pressure or wind forces

Figure 2: Construction site showing the main zones of the dam

Historical records over the last 600 years and recent instrumental observations showed that earthquakes in Ethiopia mainly occur in the Afar depression, the escarpments and the main Ethiopian rift [16, 17]. According to [12] the earthquake that occurred on 12th February 1845, is particularly of great interest to the Ribb dam site. The estimated location of the epicenter of that earthquake was within 175 km distance from the dam site, and the induced destruction was reported to be large. Based on the tremors reported in the northern parts of Ethiopia including Gondar, Wollo, parts of Gojam and parts of Shoa, the magnitude of that earthquake was estimated to be 6.0 to 6.5 in Richter scale. The dam site and the reservoir area lie in zone six of the seismic hazard map of Ethiopia [12]. Since the site is earthquake prone area, full dynamic analyses have to be carried out for important structures like the Ribb dam in addition to considerations of the worst loading conditions.

3. NUMERICAL MODELING

The use of numerical methods is allowed in international standards for the analyses of complex geotechnical structures [18, 19].The choice of a suitable numerical tool together with an appropriate constitutive model is a key for the successful simulation of such complex geotechnical problems. Most researchers have proved the appropriateness of the Finite Element Method for stability analysis of dams, especially with coupled seepage and dynamic analyses. The limit equilibrium method, on the other hand, was found to be overestimating the factor of safety as compared to the finite element method [20].

According to Akhlaghi et al [21], versatile and robust soil models should be applied to properly employ the techniques and obtain more accurate results, even though finite element method is very useful numerical technique which is widely used for the slope stability analysis.

Mohr Coulomb constitutive model is a simple elastic-perfectly plastic model which is preferred by many researchers due to its simplicity and the ability in simulating many geotechnical problems with the minimum possible parameters. The model involves five parameters, namely Young's modulus (E), Poisson's ratio (ν), cohesion (c), friction angle (ϕ), and dilatancy angle (ψ). In addition to these parameters; coefficient of permeability (k), saturated and unsaturated unit weights (γ_{sat} and γ) are also used as useful input parameters. The shear stress at failure of the Mohr - Coulomb criteria is described as below [22].

$$\tau' = c' + \sigma' \tan\phi' \tag{1}$$

where τ': shear stress at failure,

c': the cohesion,

σ': effective normal stress at failure

ϕ': effective angle of shear resistance.

The Mohr - Coulomb constitutive model has been used in modelling the static and dynamic soil structure interactions to simulate soil behaviour properly. The corresponding basic Mohr Coulomb parameters used for modelling purpose and adopted from [13] are summarized in (Table 1).

PLAXIS uses strength reduction method (SRM), to simulate failure limit state of slope and safety factor [23]. The strength reduction method is based on progressive reduction of the shear strength parameters ϕ and c, until the failure of slope prevails. Once the failure mechanism is reached, the more appropriate factor of safety is given as:

$$FS = \frac{s_{\max,\,available}}{s_{required,equil}} \qquad (1)$$

$$\Sigma Msf = \frac{\tan\phi_{input}}{\tan\phi_{reduced}} = \frac{c_{input}}{c_{reduced}} \qquad (2)$$

where: $s_{\max,\,available}$: maximum strength

$s_{required,equil}$: reduced strength in the FE computations

ΣMsf : the value of soil strength parameters

input : corresponds to the input shear strengh parameters

reduced: reduced shear strength valaues during analyses

Plastic calculation, consolidation analysis, dynamic calculation and phi-c reduction (safety analysis) were performed in accordance with the type of loading activated during the construction phases in reality. For simplicity of the analysis, the construction stages of the dam were classified in to seven phases. The elevation difference was set at 12.5 m except the first stage of construction which is 15 m below OGL as shown in (Figure 3) below.

Table 1: Basic material parameters (WWDSE, 2007a)

Upstream and downstream materials	c' [kN/m²]	ϕ' [°]	Ψ [°]	γ_{sat} [kN/m³]	γ [kN/m³]	k [m/s]	ν [-]	E [MPa]
Core material	30	14	0	18	16	$5\cdot10^{-8}$	0.322	20
First filter, F1	0	34	4	21	18	$1.21\cdot10^{-6}$	0.24	45
Second filter, F2	0	34	4	22	18	$3.2\cdot10^{-4}$	0.24	60
Shell	0	38	8	22.6	18	$1\cdot10^{-3}$	0.29	$24\cdot10^{3}$
Rock-fill	0	40	10	23	22	0.1	0.3	$38\cdot10^{3}$
Riprap	0	40	10	23	22	0.1	0.3	$44\cdot10^{3}$
Alluvial fill	0	32	2	22	18	$1\cdot10^{-3}$	0.29	$24\cdot10^{3}$
Alluvial foundation	20	13	0	18.3	17	$1.5\cdot10^{-8}$	0.31	19
Rock foundation	1000	38	8	23	22	$1\cdot10^{-7}$	0.3	$44\cdot10^{3}$

The model boundaries were set far enough to consider the stress influence zones. In order to obtain more accurate results, quartic triangular elements were used for modelling the complex problem using plane the strain analysis method. Computations of stability analyses have been performed by considering eleven different critical loading conditions shown in (Table 2).

The first two cases deal with the static analysis of the stage-wise dam construction. The next two cases consider mainly the effects of water level variations under static conditions. The remaining seven cases deal with the superimposed effects of dynamic loads and the aforementioned loads. Two earthquake magnitudes have been considered in the coupled analyses with the aim of assessing considering the most critical effects.

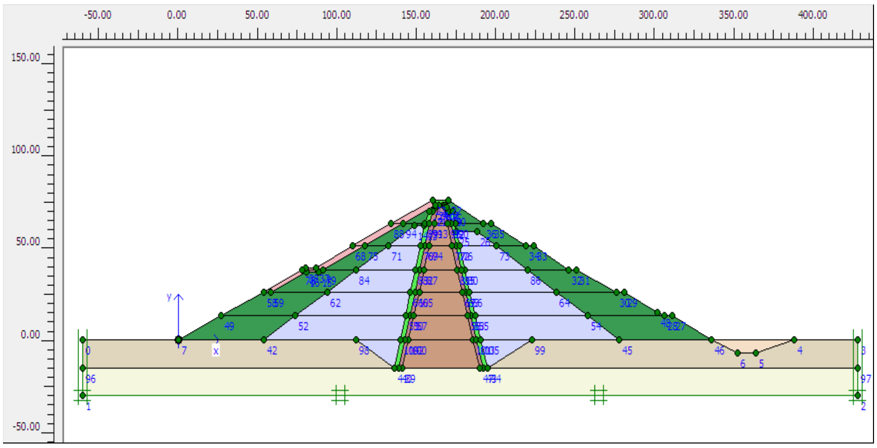

Figure 3: Geometry model of Ribb Earthen Dam

Gebregziabher & Gebrehiwot

Table 2 Calculation stages and types of analysis

Cases	Calculation stages	Type of analysis
1	Second stage end of construction (12.5 m above Original Ground Level, OGL)	Static analysis
2	End of construction (75 m above OGL)	Static analysis
3	Steady state, Normal Water Level (NWL)	Static analysis
4	Rapid drawdown	Static analysis
5	Second stage end of construction	Dynamic analysis (M = 6.5)
6	End of construction	Dynamic analysis (M = 6.5)
7	Steady State	Dynamic analysis (M = 6.5)
8	Rapid drawdown	Dynamic analysis (M = 6.5)
9	End of construction	Dynamic analysis (M = 4.5)
10	Steady state	Dynamic analysis (M = 4.5)
11	Rapid drawdown	dynamic analysis (M = 4.5)

4. RESULTS AND DISCUSSION

The advantage of stress-strain modelling using Finite Element Analysis is that it gives the most accurate picture of what actually happens in the region during any loading conditions [7, 23]. Since the finite element method is a good analysis method of maintaining force equilibrium, compatibility equation, constitutive equations and simulation of actual slope failure with the minimum possible assumptions, a value of factor of safety greater than 1.0 indicates that the capacity will not be exceeded and that the slope will be stable [24]. FOS of 1.0 can be dynamically stable based on the FE deformation analyses [23] and the deformation calculated along the failure plane should not generally exceed 1 m [20]. Based on the performance of an earth filled dam, it is recommended that the settlement of the crest should not exceed 1.0 m [25, 26].

During the static analysis of Ribb earthen dam, the FEM model showed that, the safety factor decreases with increase in load cases described in (Table 2), as it might be expected; i.e. case one > case two > case three > case four >1. The minimum FOS of 1.035 is obtained when the water level in the reservoir reduces quickly (case four), which is just above 1. The safety analysis results of all critical loading conditions at static cases are summarized in (Table 3) below.

The factor of safety (FOS) in all the static load cases is greater than 1.0 and the total displacements are within centimeter ranges, which is within the permissible limits of international standards for the likely cases of failure of the dam to happen [26]. In addition to this, the phreatic line has been found to emerge below the toe of the dam as shown in (Figure 4); indicating that, the dam is safe against piping and sloughing, which are the main causes of failure of most downstream faces of dams.

The maximum ground acceleration (PGA = 0.12g) that had occurred around the site on 12th February, 1845 was used to consider the effects of the earthquake loading on the stability of the dam. According to WWDSE, the site is located under seismic zone of IV and VI. Accordingly, two earth quake magnitudes; namely, a maximum horizontal ground motion (PGA=6.5 Richter scale) that happened in the past history around the site and an earthquake of 4.5 magnitude, which accounts for the more frequently occurring shock were considered. The results of the safety analyses of all coupled critical loading conditions by considering the two Earthquake magnitudes are summarized in (Table 4).

All the analyzed safety factors, deformations, and displacements are safe at all critical loading conditions including both dynamic load cases, except when the maximum earthquake and rapid drawdown occur simultaneously; in which case, the safety factor lowers to 0.996, as shown in (Figure 4)

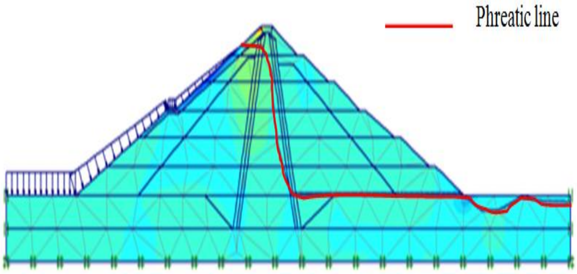

Figure 4: Location of phreatic line during case three

Table 3 Summarized results (FOS) of static analysis

No.	Loading condition	FOS static
1	Case1:(Second stage end of Construction i.e. at 12.5 m above OGL)	1.317
2	Case 2: End of Construction (75 m above OGL)	1.169
3	Case 3: Steady State (NWL)	1.132
4	Case 4: Rapid Drawdown	1.035

Table 4 Summarized results of dynamic analysis

No	Loading condition	FOS
1	Case five: (Second stage end of construction coupled with Dynamic Analysis (M = 6.5)	1.292
2	Case nine: End of Construction with Dynamic Analysis (M = 4.5)	1.128
	Case six: End of Construction with Dynamic Analysis (M = 6.5)	1.118
3	Case ten: Steady State with Dynamic Analysis (M = 4.5)	1.115
	Case seven: Steady State with Dynamic Analysis (M = 6.5)	1.017
4	Case eleven: Rapid Drawdown with Dynamic Analysis (M = 4.5)	1.021
	Case eight: Rapid Drawdown with Dynamic Analysis (M = 6.5)	0.996≈1

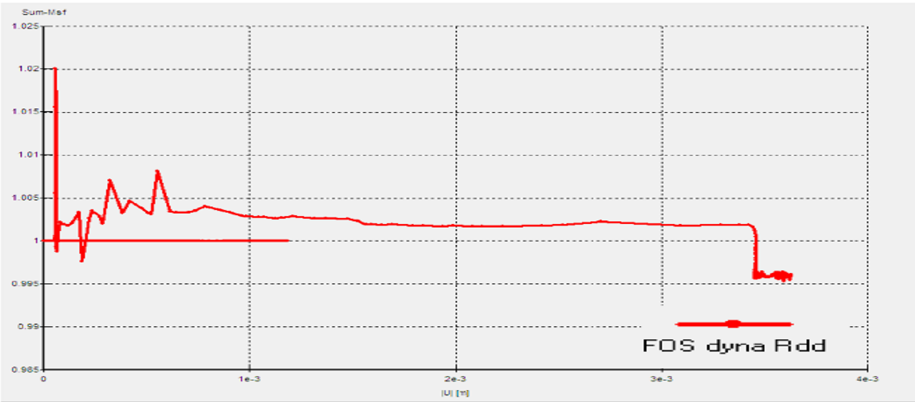

Figure 1: Plot of FOS during rapid drawdown and dynamic loading

The maximum unstable condition occurs when rapid drawdown condition is coupled with the dynamic loading cases. The minimum FOS obtained at the earthquake magnitude of 6.5 is found to be just below one. Since the probability of occurrence of the maximum dynamic loading simultaneously with the rapid drawdown condition is very low in the design life of the dam, it can be considered to be safe under the given conditions.

5. CONCLUSION

In the present study, slope stability of the Ribb earthen dam in Ethiopia under different loading conditions has been investigated. Deformation analysis and seepage through the main body of the dam and foundation have been carried out for both static and dynamic loading conditions by using Finite Element Method employing the strength reduction strategy of PLAXIS to compute the FOS. The results of the FEM analyses showed that, the dam is stable under static and dynamic load cases and at different water level conditions. Since the phreatic line lies under the toe of the dam satisfying the standard design criteria, assuring the safety against piping and sloughing problems, the dam safety is not endangered by seepage. All the deformations are within the permissible limits of standards and no possibility of internal erosion due to seepage will occur.

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